Performance of Earthquake Damage Beams Repaired via Epoxy Injection

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Introduction

On 14 November 2016, the Mw 7.8 Kaikoura Earthquake, struck the North-Eastern region of the South Island of New Zealand. With an epicentre approximately 100km north of Christchurch, the earthquake resulted in fault rupture propagating north, with surface expression extending approximately 150km. The ground shaking was felt in many regions of New Zealand and even resulted in accelerations exceeding design levels for certain periods in the Wellington region of the North Island (Bradley et al., 2017). Most ductile RC moment frame structures performed as intended, with the formation of beam plastic hinges ranging from minor to moderate damage states being observed (Henry et al., 2017). A prominent challenge for engineers, highlighted by the Kaikoura earthquake was assessing the residual capacity and repairability of plastic hinges in low to moderately damaged RC structures. The lack of guidelines left engineers with little technical backing to assess the residual capacity of RC structures damaged in the earthquake. Following the earthquake an opportunity was provided to extract and test directly the residual capacity and the effectiveness of simple repair techniques on the performance of damaged RC beams. The tests investigate the use of epoxy crack injection, a relatively quick and simple to apply repair technique which, if effective, would allow moderately damaged RC structures to return to normal function in a short period of time.

Testing of Extracted Beam Specimens

Specimen Details and Post Earthquake Damage

Two internal and two external beam-column (b/c) joints were removed from the fourth floor above ground of a RC perimeter frame structure. The building was designed to a ductility of 6 and was expected to have gone through inelastic behaviour during the Kaikoura earthquake. All steel reinforcement was grade 300E with a specified concrete strength of 25MPa. The longitudinal reinforcement ratio, ρ_t, of all specimens was 0.6%. The beams spanned ~4.8m between the column faces in the frame and satisfy all detailing requirements of NZS 3101:2006-A3. External b/c joints had cracking in the plastic hinge region up to 5mm wide with some cover spalling, while internal joints had hairline cracking with only one major crack adjacent to the joint region up to 2mm wide.

Experimental Methodology

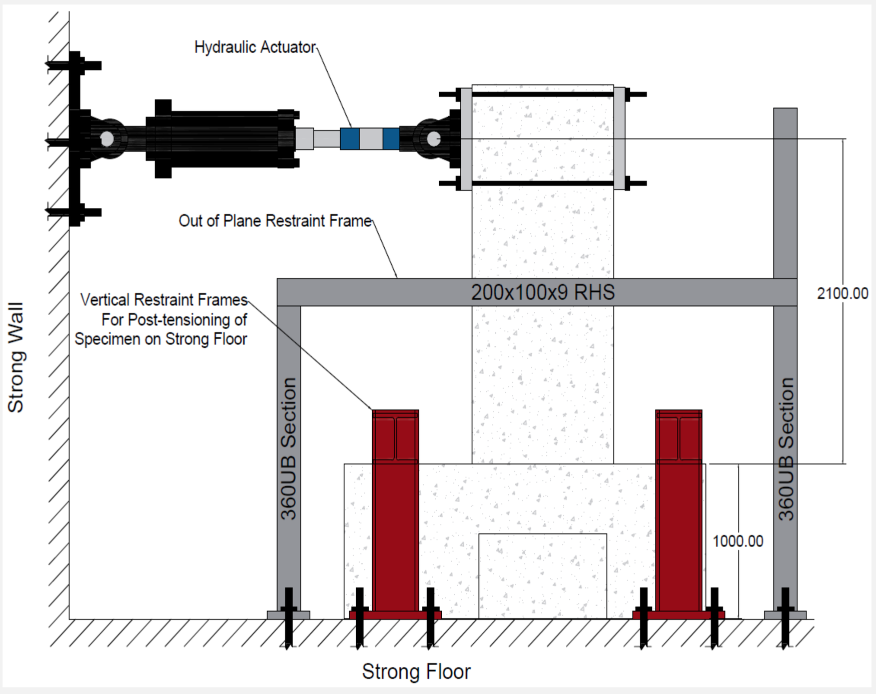

Figure 1: Cantilever Beam Testing Configuration.

- ❑ All four beams were tested in a cantilevered configuration as seen in Figure 1.
- ❑ Custom steel frames were post-tensioned onto the surface of the columns to clamp down specimens onto the strong floor.
- ❑ 2000 kN hydraulic actuator was used to apply load at a height of 2.1m above the foundation.
- ❑ Load span to depth ratio for all four beams was equal to 2.1.
- ❑ An out of plane restraint frame was installed around the beam during testing.

Loading Protocol

Specimen ID	Repair (Y/N)	Loading Protocol
E-U	N	Standard Cyclic
E-R	Y	Standard Cyclic
I-1.5-U	N	Standard Cyclic with pre-cycles at 1.5% Drift
I-3.0-U	N	Standard Cyclic with pre-cycles at 3.0%

Notes: The notation U and R in specimen IDs represents Unrepaired and Repaired, respectively. The notation E and I in specimen IDs represents External and Internal beams, respectively.

- ❑ A standard cyclic loading protocol was applied in some form to all four specimens
- ❑ External b/c joint E-R was repaired and tested via epoxy injection and epoxy mortar repair (Fig. 2).
- ❑ External b/c joint E-U was tested with existing earthquake damage.
- ❑ Internal b/c joint I-1.5-U was tested by applying 4 cycles at 1.5% (equivalent to Kaikoura demand) prior to standard cyclic loading.
- ❑ Internal b/c joint I-3.0-U was tested by applying 4 cycles at 3% prior to standard cyclic loading.

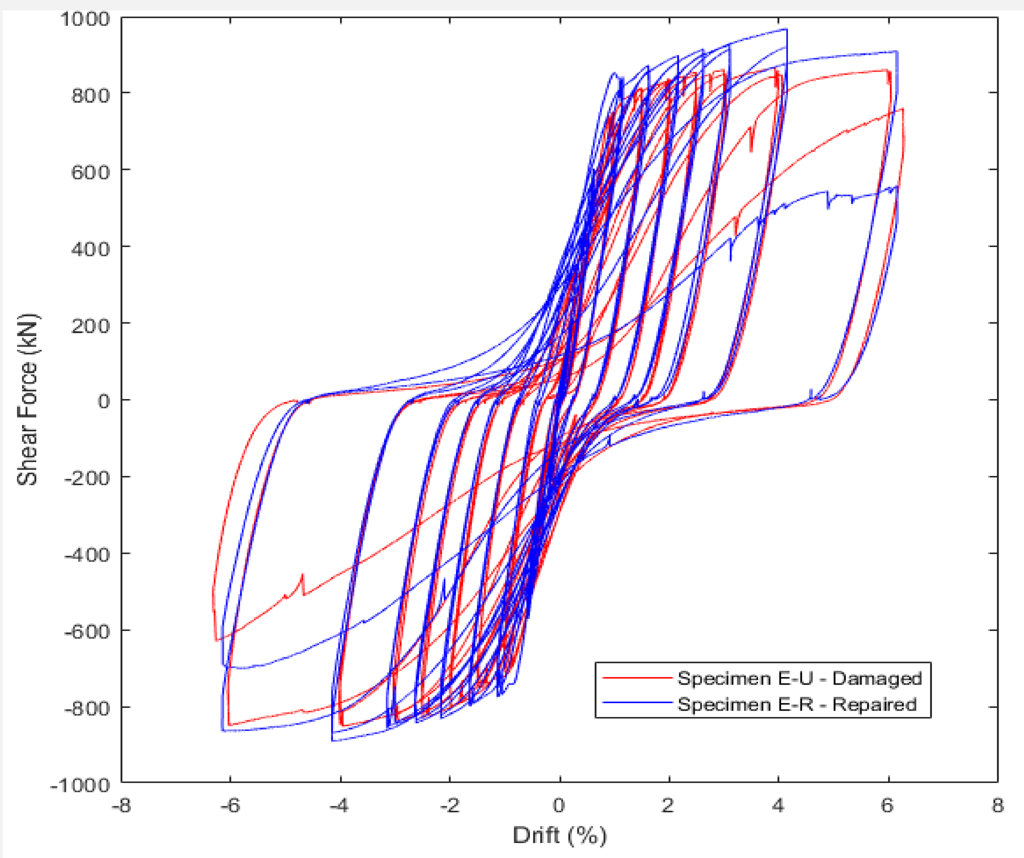

Figure 2: Hysteresis Plots for Specimen E-U (Red) and E-R (Blue).

Experimental Results

- ❑ Specimens saw significant spalling at 4% drift with signs of core crushing. Following cycles to 6% drift buckling of longitudinal reinforcement was also evident. All specimens saw a 20% drop in strength on the second cycle to -6% drift coinciding with the unhooking of the stirrups. No bar fracture was observed (See Figure 2 for comparison of hysteresis for specimen E-U and E-R).
- ❑ Specimens showed consistent damage progression, with significant diagonal shear cracking in the plastic hinge region, similar to the in-situ earthquake damage (Fig. 3).
- ❑ Failure drift is approximately twice the drift capacity of 2.8% calculated according to NZS 3101:2006-A3 (using K_d = 19).
- ❑ Lightly damaged internal b/c joints had a secant stiffness to yield ~45% higher than the more heavily damaged external joint.
- ❑ The repaired specimen E-R had a 26% increase in secant stiffness to yield compared to its unrepaired counterpart, E-U.
- ❑ The repaired specimen had a yield strength ~10% higher than the unrepaired specimens and ~25% higher than the predicted overstrength, likely as a result of the strain aging phenomenon of the Grade 300E reinforcement.

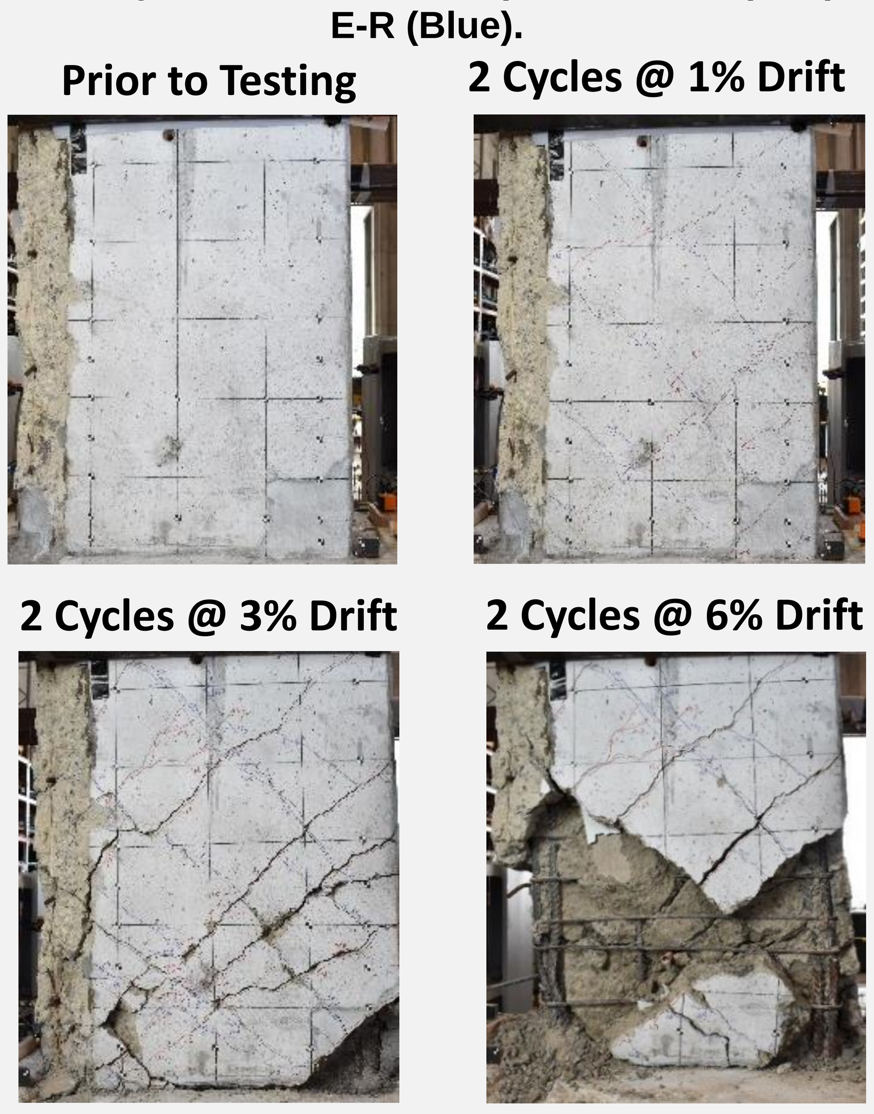

Figure 3: Damage Progression for Specimen E-R, Indicative of all specimens.

Conclusions

Four beam-column joints were extracted from a damaged RC building in Wellington following the 2016 Kaikoura Earthquake. The specimens were tested at the University of Auckland. The key results of the experimental testing are outlined below.

Stiffness:

- ❑ Repair via epoxy Injection resulted in an increase in secant stiffness to yield of 26% .
- ❑ Unrepaired Specimens had a stiffness ~25% of assumed design stiffness based on NZS 3101:2006.

Strength and Drift Capacity:

- ❑ All specimens displayed yield strength above predicted overstrength as a result of the strain ageing phenomenon.
- ❑ Repaired Specimen saw up to 10% increase in yield and ultimate strength in comparison to the average of unrepaired specimens.
- ❑ All specimens failed at 6% drift with no bar fracture observed and no change in displacement capacity due to additional large amplitude cycles.

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